Bottom-up naturalness

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with

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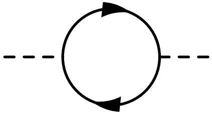
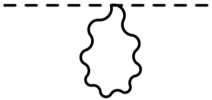
The hierarchy problem

- The Higgs mass in the SM is not protected by symmetries
- One loop contributions quadratically divergent (top, gauge)
- Mass corrections of order the cutoff scale Λ^2
- New physics at the TeV scale



$\propto \quad -m_t^2\Lambda^2$



$\propto \quad +m_V^2\Lambda^2$

Traditional approaches

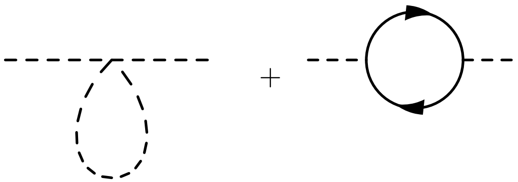
Top down approaches

Assuming a high energy mechanism which cancels the divergences at all loop levels

- SUSY
- Extra dimensions
- Little Higgs
- ...

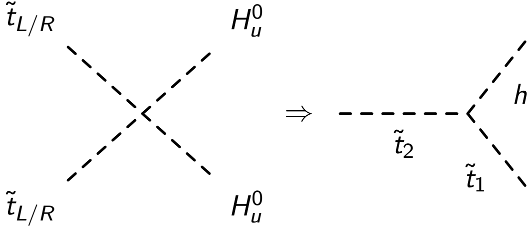
Traditional approaches

New particles running in loops



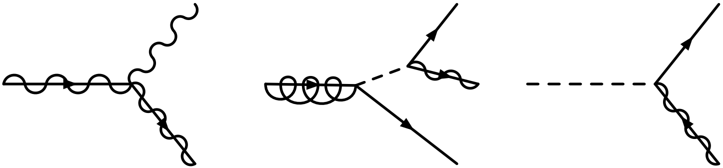
$\propto \log \Lambda$

Cancellation terms give new signatures



Traditional approaches

But dominant signatures from other terms



Model dependent

Not directly related to the quadratic divergences

Bottom up approach?

Study low energy signatures of naturalness

$\Rightarrow$ Cancellation at one loop only

$\Rightarrow$ No complete model

But

$\Rightarrow$ Necessary conditions for naturalness

$\Rightarrow$ Model independent approach

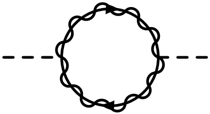
$\Rightarrow$ Hints for new complete theories?

$\Rightarrow$ Limited number of simplified models

Minimal naturalness

Naturalness is enforced by

$y' H \psi_1 \psi_2$ $\lambda H^\dagger H \psi^\dagger \psi$

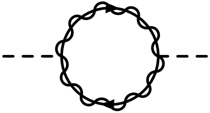


- Find all possible ψ
- For each ψ, look for signatures which vanish when y or λ vanishes

The trilinear term

Properties of ψ_1, ψ_2

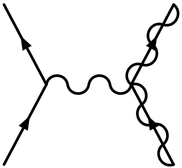
$$\mathcal{L} = yH\psi_1\psi_2$$

 $\propto -y^2\Lambda^2$

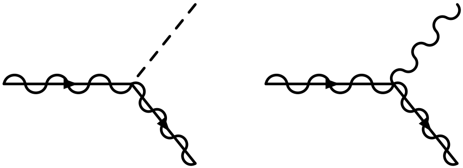
- ψ_1 and ψ_2 are fermions
- Negative one loop contribution
- ψ_1 and/or ψ_2 charged under **at least** $SU(2)$

Trilinear term – ψ_1 and ψ_2 non SM

- If no other term, ψ_1 or ψ_2 stable
- **Electroweakino-like phenomenology**

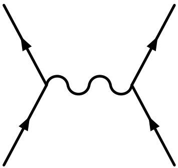


- Decays to Higgs and gauge bosons
- $\not{E}_T$, CHAMPs, R-hadrons...

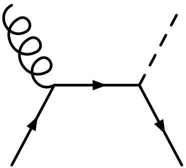


Trilinear term – ψ_1 is SM

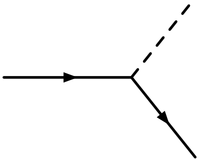
- ψ_2 has the same quantum number as a SM particle
- Fourth generation of quarks or leptons



Electroweak/strong production



Associated production $\propto y^2$



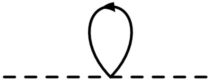
Decay to W, Z, h $\propto y^2$

The quartic term

The quartic term

$$\mathcal{L}_2 = \lambda H^\dagger H \psi^\dagger \psi$$
$$\supset \lambda v h \psi^\dagger \psi + \frac{\lambda}{2} h^2 \psi^\dagger \psi$$

Scalar



Vector-like fermion

- New Higgs decay modes
- ψ is a dark matter particle
- ψ gets a vev
- ψ is charged under the SM

The quartic term

$$\mathcal{L}_2 = \lambda H^\dagger H \psi^\dagger \psi$$
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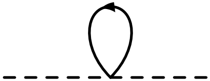

Vector-like fermion

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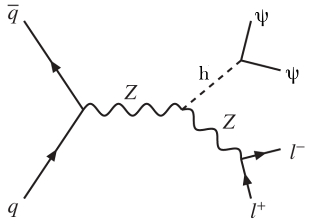
Higgs decays to $\psi^\dagger\psi$



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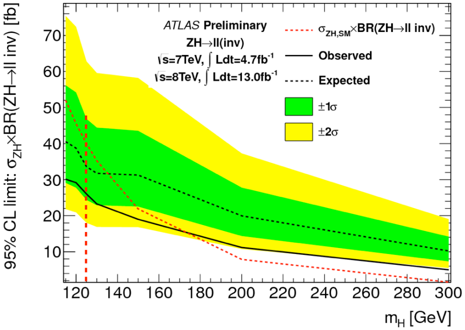

- Invisible decay modes
- Top and gauge divergences ⇒ Excluded
- Other divergences ⇒ Effect too small

The quartic term

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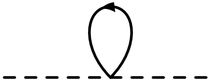
$$\supset \lambda v h \psi^\dagger \psi + \frac{\lambda}{2} h^2 \psi^\dagger \psi$$

Scalar



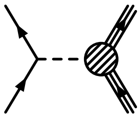
Vector-like fermion

- ~~New Higgs decay modes~~
- ψ is a dark matter particle
- ψ gets a vev
- ψ is charged under the SM

ψ is dark matter

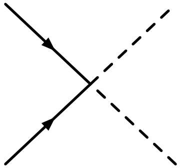
Assuming interactions with the SM only through the quartic

Direct detection



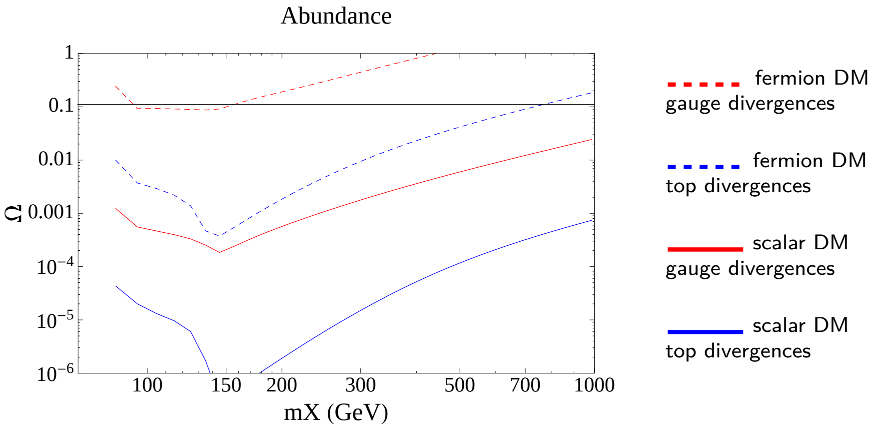
Spin independent interactions
Higgs portal only

Annihilation



$\psi\psi \to hh$, WW, ZZ

Relic abundance



Non thermal production

Indirect detection

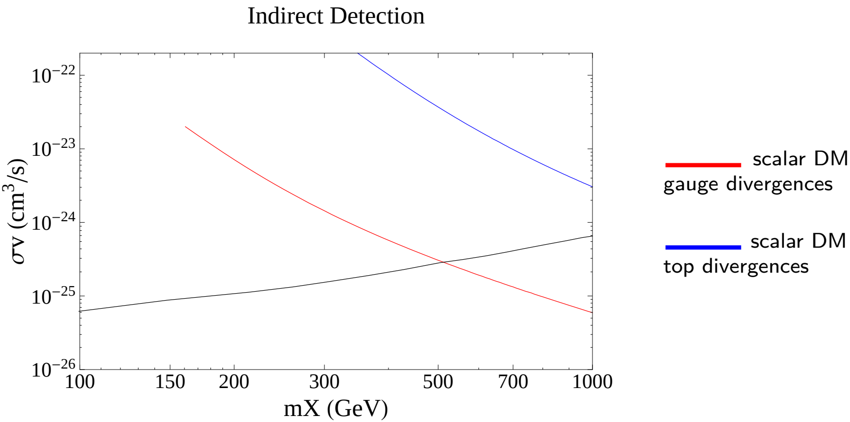
$$\lambda\psi^\dagger\psi H^\dagger H \supset \frac{\lambda}{2}\psi^\dagger\psi hh + \lambda\psi^\dagger\psi\psi^+\psi^-$$

$$\left.\begin{aligned} \psi^\dagger\psi &\to hh \to \text{bottoms} \\ \psi^\dagger\psi &\to W^+W^- \end{aligned}\right\} \to \text{pions} \to \text{photons}$$

- Large mass/Low velocity annihilation cross sections

$$\langle\sigma_{\text{fermion}} v\rangle_{v=0} = 0$$
$$\langle\sigma_{\text{scalar}} v\rangle_{v=0} = \frac{9y_t^4}{16\pi m_\psi^2},\ \frac{9g^4}{16\pi m_\psi^2},\ \ldots$$

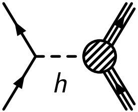
Indirect detection



- No top quadratic divergences cancellation
- Gauge cancellation possible for $m_\psi > 500\,\mathrm{GeV}$

Direct detection

$$\lambda \psi^\dagger \psi H^\dagger H \supset \lambda v\, h\, \psi^\dagger \psi$$

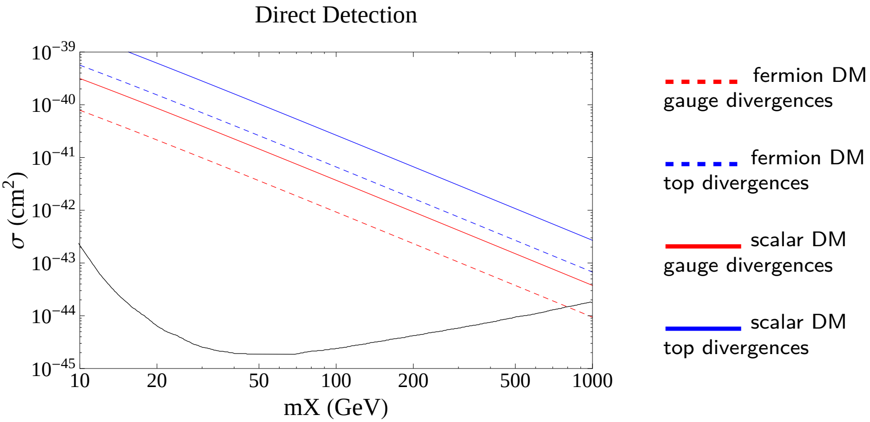


$$\sigma_{\rm SI} = \frac{a}{\pi} \frac{m_p^2}{(m_\psi + m_p)^2} \frac{9 y_t^4 m_p^2}{m_h^4} f^2$$

$$f = \frac{6}{27} + \frac{21}{27} \left(f_{Tu} + f_{Td} + f_{Ts} \right)$$

$$a = \begin{cases} 4 & \text{real scalar} \\ 1 & \text{complex scalar} \\ & \text{majorana fermion} \\ \frac{1}{4} & \text{dirac fermion} \end{cases}$$

Direct detection



- Top and gauge cancellation excluded

ψ dark matter

Correlated direct and indirect detection signatures

- If fermion, direct detection signature but no indirect detection signal
- If scalar,

$$\frac{\sigma_{\rm SI}}{\langle \sigma v \rangle_{v=0}} = \frac{16 f^2 m_p^2}{m_h^4} = 1.5 \times 10^{-19} \frac{\rm cm^2}{\rm cm^3/s}$$

Measurable at FERMI, XENON100, LUX

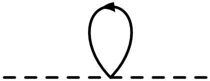
Sub-TeV ψ cannot cancel the top quadratic divergences

Small region still left for gauge quadratic divergences

The quartic term

$$\mathcal{L}_2 = \lambda H^\dagger H \psi^\dagger \psi$$
$$\supset \lambda v h \psi^\dagger \psi + \frac{\lambda}{2} h^2 \psi^\dagger \psi$$

Scalar



Vector-like fermion

- ~~New Higgs decay modes~~
- ~~ψ is a dark matter particle~~
- ψ gets a vev
- ψ is charged under the SM

Scalar with a vev

$$\mathcal{L} = \lambda v v_\psi h\psi + \frac{\lambda}{2} v_\psi \psi hh + \frac{\lambda}{2} vh\psi\psi + \dots$$

- Mixing with the Higgs
- ψ decays
- h decays (already studied)

If ψ is an $SU(2)$ doublet $\Rightarrow$ two Higgs doublet model

What about a singlet?

Singlet ψ with a vev

$$\mathcal{L} \supset \frac{\lambda}{2} v_\psi v\, h\, \psi \quad \Rightarrow \quad \begin{pmatrix} h_m \\ \psi_m \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ \psi \end{pmatrix}$$

Higgs couplings uniformely suppressed

$$\sigma^H_{\rm prod} = \cos^2\alpha\, \sigma^H_{\rm SM}$$

$$\mathrm{Br}(h \to AB) = \mathrm{Br}_{\rm SM}(h \to AB)$$

Singlet ψ with a vev

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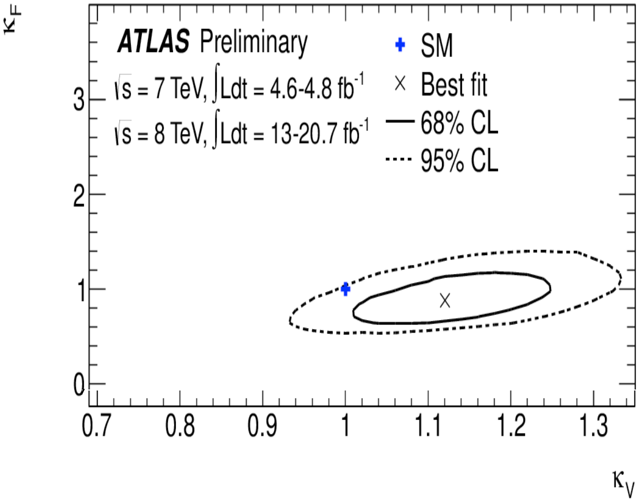

$\kappa_F = \kappa_V = \cos\alpha$

$\cos\alpha > 0.93$

Heavy ψ with a vev

If $m_\psi \geq 2m_{h,W,Z}$

$$\lambda \psi^\dagger \psi H^\dagger H \supset \lambda v_\psi \psi h^\dagger h$$

$$\psi \to \begin{cases} hh & 25\% \\ ZZ & 25\% \\ W^+W^- & 50\% \end{cases} \quad \text{for large } m_\psi$$

- Heavy Higgs search $H \to ZZ \to llll$ most sensitive

$$\mathrm{Br}_{\mathrm{SM}}(H \to ZZ) \sim 30\%$$

Heavy ψ with a vev

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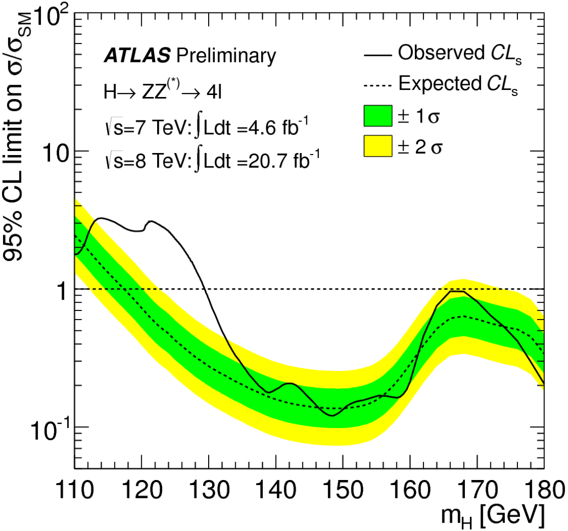


$$\mu \sim \frac{\sigma^{\psi}_{\mathrm{prod}}}{\sigma^{H}_{\mathrm{SM}}} \sim \sin^2\alpha$$

Best bounds

$\sin^2\alpha \leq 10\%$

Very specific masses

Scalar with a vev

- Mass mixing with the SM Higgs
- If ψ is a singlet, $\cos\alpha$ suppression of the SM Higgs couplings

$$\cos\alpha > 0.93$$

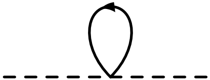
- If $m_\psi > 2m_{h,W,Z}$, decays to hh, W^+W^- and ZZ
- Bounds from heavy Higgs searches less competitive than precision Higgs physics
- For our minimal model, top cancellation requires

$$v_\psi > 2\,\mathrm{TeV}$$

The quartic term

$$\mathcal{L}_2 = \lambda H^\dagger H \psi^\dagger \psi$$
$$\supset \lambda v h \psi^\dagger \psi + \frac{\lambda}{2} h^2 \psi^\dagger \psi$$

Scalar

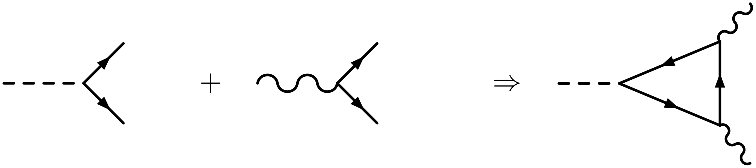


Vector-like fermion

- ~~New Higgs decay modes~~
- ~~ψ is a dark matter particle~~
- ~~ψ gets a vev~~
- ψ is charged under the SM

ψ charged under the SM

$$\mathcal{L} \supset \lambda h \psi^\dagger \psi + g_{\mathcal{G}} V_{\mathcal{G}}^{\mu} \gamma_\mu \psi^\dagger \psi$$



- One loop Higgs couplings to gauge bosons modified

$SU(3)$	production, not visible
$SU(2)$	decay, hard to reach at the LHC
$U(1)_{\mathrm{EM}}$	decay, high luminosity LHC

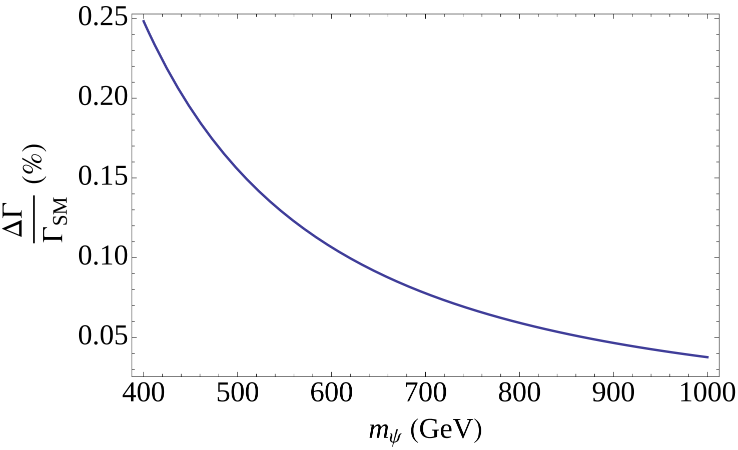
Example: electrically charged ψ

ψ has electric charge Q and cancels the top quadratic divergences

$$\mathcal{L} \supset -m\psi^\dagger\psi + \frac{3y_t^2}{2m}\psi^\dagger\psi hh$$

$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma_{\mathrm{SM}}(h\to\gamma\gamma)} = \left|1 + \frac{Q^2}{6.49}\frac{4}{3}\frac{\partial \log m_\psi}{\partial \log v}\left(1+\frac{7m_h^2}{120m_\psi^2}\right)\right|^2$$

Example: electrically charged ψ



Less than 10% modifications at high mass

Quartic term: summary

$$\lambda\psi^\dagger\psi H^\dagger H \supset \begin{cases} \lambda v h\psi^\dagger\psi + \frac{\lambda}{2} hh\psi^\dagger\psi \\ \frac{\lambda}{2} v v_\psi h\psi + \lambda v h\psi^\dagger\psi + \lambda v_\psi \psi hh \end{cases}$$

- ψ light
  - Invisible Higgs decays
  - Cannot cancel top and gauge quadratic divergences
- ψ dark matter
  - Correlated direct and indirect detection signatures
  - Strong constraints on top and gauge divergences cancellation
- ψ scalar with a vev
  - Precision Higgs coupling measurements
  - Tight constraints on v_ψ
- ψ charged under the SM
  - One loop contributions to $h \to VV$
  - Modifications too small to observe with current searches

Current prospects

- Strong constraints in specific cases for top and gauge cancellation (dark matter, light particle, etc...)
- In most cases, precision Higgs measurements are needed

Most minimal signatures cannot be observed with current experiments!

Can some simple extensions be probed at the LHC?

Finding minimal extensions

Minimal naturalness – Quartic term extension

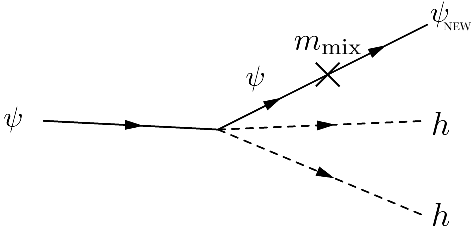
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \lambda H^\dagger H \psi^\dagger \psi$$

Find additional terms:

- IR effect
- No assumptions about the UV physics
- New decay modes for ψ, new LHC signatures
- **Signatures vanish when $\lambda \to 0$**

Only possible term

$$\mathcal{L} \supset m_0 \psi^\dagger \psi_{\text{NEW}}$$



$$\psi_{\text{NEW}} \begin{cases} \text{Higgs boson} \Rightarrow \text{2HDM} \\ \text{Stable new particle } \Rightarrow \not{E}_T\text{, CHAMPs, R-hadrons} \\ \text{SM fermion} \end{cases}$$

Mass mixing

$$\mathcal{L} \supset \lambda_1 \psi^\dagger \psi H^\dagger H + \lambda_2 \psi^\dagger \psi_{\mathrm{NEW}} H^\dagger H$$

- Measuring λ_2
  $\Rightarrow$ **Indirect** evidence of λ_1
- Three-body decays to ψ_{NEW}, WW, hh and ZZ
- Two-body decay to ψ_{NEW} and h
- NO two-body decays to gauge bosons

Example: Little Higgs model

Fermionic top partner

$$\mathcal{L} = m_\psi \psi\psi^c + \lambda_1 \psi^c HQ + \lambda_2 u^c HQ + \frac{\lambda_3}{m_\psi} \psi\psi^c H^\dagger H$$

In mass basis

$$\begin{aligned}\mathcal{L} &= m_T TT^c + \lambda_T T^c HQ + y_t u^c HQ \\ &+ \frac{\lambda_{TT}}{m_T} T^c TH^\dagger H + \frac{\lambda_{tT}}{m_T} u^c TH^\dagger H\end{aligned}$$

- λ_{tT} generated by λ_{TT} and mass mixing

Example: Little Higgs model

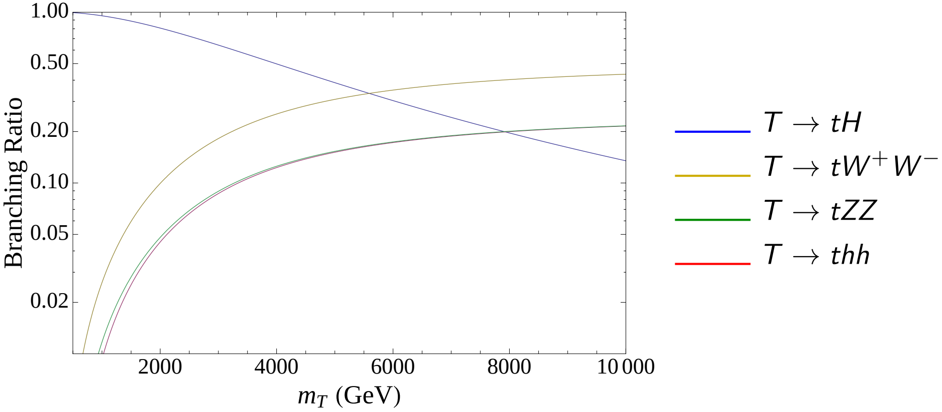
$$\mathcal{L} \supset \lambda_T T^c HQ + \frac{\lambda_{tT}}{m_T} u^c TH^\dagger H$$

- Two-body decays from trilinear + quartic terms
- λ_T usually expected to dominate
- But two-body signatures dominantly from quartic if

$$\lambda_{tT} > \lambda_T \frac{m_T}{v}$$

Little Higgs is a good example for large quartic and moderate m_T

T decay modes



$T \to tH$ largely dominating

Vector-like fermions at the LHC

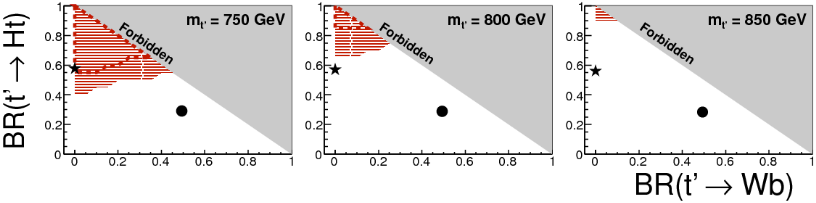
$$\mathcal{L} \supset \lambda \psi \psi_{\mathrm{NEW}} H^\dagger H \supset \lambda_1 \psi \psi_{\mathrm{NEW}} h$$

- Choose ψ_{NEW} SM fermion
- Consider only two-body decays
- Derive bounds for top quark, light quark and lepton partners

$$T \to t + h$$
$$U \to u + h$$
$$L \to l + h$$

Top quark partners

- ATLAS-CONF-2013-018
- 8 TeV, $14.3\mathrm{fb}^{-1}$



- $\mathrm{Br}(T \to th) = 100\% \Rightarrow m_T > 850\,\mathrm{GeV}$

Light quark partner

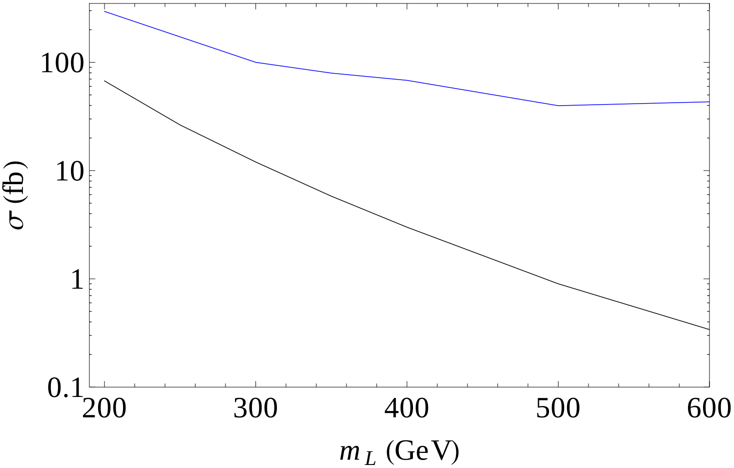
- *hhjj* final state
- No rapidity gap between the two jets
- Low branching ratio to leptons + low lepton ID efficiency
- $h \to \gamma\gamma$ search does not veto on extra jets
- Current bounds on $\gamma\gamma$ allow up to $10\,\mathrm{pb}$ signal

$$m_U > 300\,\mathrm{GeV}$$

Lepton partner

- $l^+ l^- hh$ final state
- $l^+ l^- + 2b$ dominant but existing searches require an on-shell Z
- 4-lepton events from $h \to W^+ W^-, \tau\tau$
- ATLAS-CONF-2013-036
- 4-leptons + effective mass cut
- Low background, high signal efficiency

Lepton partner

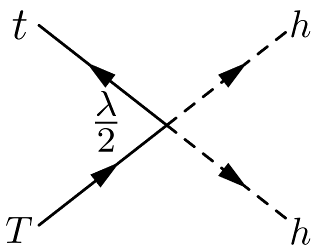


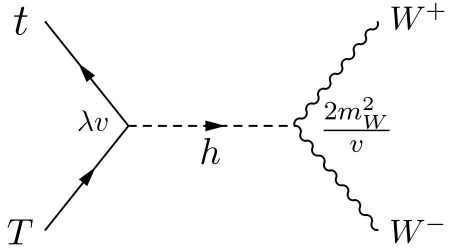
Low production cross section $\Rightarrow$ no exclusion bounds

Summary

- Two possible operators to cancel one-loop divergences
- Bottom-up approach: study signatures which vanish when these operators vanish
- New Yukawa term $\Rightarrow$ electroweakino phenomenology, CHAMPs, R-hadrons
- Quartic term
  - Correlated dark matter detection signatures
  - Higgs precision measurements
- Mass mixing with a SM fermion gives new decay modes
- Only one two-body decay mode to SM fermion + Higgs
- Strong bounds on top partners at the LHC, high luminosity + dedicated searches needed for the other particles

Goldstone boson equivalence theorem





$$|M(T \to thh)|^2 \sim \frac{\lambda^2}{2} p_{T,\mu} p_t^\mu$$

$$|M(T \to tW^+W^-)|^2 \sim 4\lambda^2 m_W^4 p_{T,\mu} p_t^\mu \frac{1}{((p_T - p_t)^2 - m_h^2)^2} \frac{(p_{W^+} \cdot p_{W^-})^2}{m_W^4}$$

Little Higgs model

$$\Sigma = \exp\left(\frac{i}{f}\begin{pmatrix} 0 & H \\ H^\dagger & 0 \end{pmatrix}\right)\begin{pmatrix} 0 \\ f \end{pmatrix}$$

After symmetry breaking

$$\mathcal{L} \supset \lambda_1 u_3^c \Sigma \chi + \lambda_2 f u'^c u'$$

At lowest order

$$\mathcal{L} \supset f(\lambda_1 u_3^3 + \lambda_2 u'^c)u' - \lambda_1 u_3^c H Q_3 + \frac{\lambda_1}{2f} H H^\dagger u_3^c u'$$

Little Higgs model

After diagonalization

$$\mathcal{L} \supset \frac{\lambda_1\lambda_2}{\sqrt{\lambda_1^2+\lambda_2^2}} t_3^c H Q_3 + \frac{\lambda_1^2}{\sqrt{\lambda_1^2+\lambda_2^2}} T^c H Q_3 + \frac{\lambda_1^2}{2m_T} H H^\dagger T^c T + \frac{\lambda_1\lambda_2}{2m_T} H H^\dagger t_3^c T$$

Two body decays from the quartic term dominate if

$$\frac{\lambda_2^2 v}{\sqrt{2} y m_T} \gg 1$$